

**Performance of the extremophilic enzyme *BglA* in the hydrolysis of two aroma glucosides in a range of model and real wines and juices.**

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**ABSTRACT**

$\beta$ -Glycosidases enhance wine aroma by releasing volatile aglycones from non-volatile glycosides. Commercial preparations contain primarily pectinases and only display  $\beta$ -glycosidase as a secondary activity which limits their potential. Here, the extremophilic  $\beta$ -glucosidase A from *Halothermothrix orenii*, (*BglA*) has been compared with Rapidase<sup>®</sup> for the production of aromatic wines and in the remediation of smoke-tainted wines. Model systems as well as real juices and wines have been enriched with geranyl glucoside, typical of white varieties, and guaiacyl glucoside, commonly found in red wines exposed to oak and wines made from grapes exposed to smoke. The hydrolytic capacity

of *BglA* was evaluated by measuring the released volatiles in the gas phase with Solid Phase Microextraction and GC-MS. *BglA*, despite an apparent instability at low pHs, is twice as effective in the release of volatiles in sweeter wines and in grape juices offering an excellent alternative for the early stages of the winemaking process and in the juice industry.

**Keywords:** Enzyme, Glucosides, Wine, Monoterpenes, Aroma, GC-MS, SPME

## 1 Introduction

Aroma is considered a key aspect of wine quality. Despite the identification of over 800 aroma compounds (Rapp, 1990) only a small number of them contribute substantially to the aroma of wine (Francis & Newton, 2005; Loscos, Hernández-Orte, Cacho, & Ferreira, 2009). Among the volatiles that are important to the aroma of wine there are fruity and floral monoterpenes (geraniol, linalool and  $\alpha$ -terpineol) and volatile phenols (guaiacol and cresols), which, depending on their concentration and wine style, could affect differently the overall flavour and aroma.

Monoterpenes, formed in grapes during ripening, are crucial components of the varietal wine bouquet of Muscat and floral varieties (Sánchez Palomo, Pérez-Coello, Díaz-Maroto, González Viñas, & Cabezudo, 2006) but a major fraction is entrapped as flavourless, odourless, non-volatile glycosides, constituting an important reservoir of aroma (Skouroumounis, Massy-Westropp, Sefton, & Williams, 1995). Monoterpenes can be liberated from their glycosides by acid or enzymatic hydrolysis; but as acid hydrolysis is a slower process (Mojsov, Andronikov, Janevski, Jordeva, & Zezova, 2015; Wilkowska & Pogorzelski, 2017) and can cause rearrangements of the released aglycones, enzymes represent a useful alternative and can be added to maximize the aromatic potential of wines (González-Pombo, Fariña, Carrau, Batista-Viera, & Brena, 2014; Günata, Dugelay, Sapis, Baumes, & Bayonove 1993).

Phenolic glycosides are also formed when berries are exposed to smoke from bush fires and prescribed forest burns as the grapevines can uptake smoke constituents like guaiacols, cresols and

50 syringols, and accumulate them in the form of glycoconjugates. However in this case, their hydrolysis  
51 leads to the release of volatile phenols (VP) giving the wine a “smoky” or “ashy” aroma/flavour  
52 (Hayasaka, Dungey, Baldock, Kennison, & Wilkinson, 2010; Mayr et al., 2014; Singh et al., 2011).  
53 In addition, breakdown of glycosides of volatile phenols in the mouth, mediated by enzymes of the  
54 oral microflora can also contribute to smoky and ashy aftertaste (Parker et al., 2012). In this case, if  
55 enzymatic hydrolysis can be performed effectively during the wine processing, phenolic glycosides  
56 can be reduced, and the release of VPs can then be minimised using different techniques (van der  
57 Hulst et al., 2019), improving the overall flavour.

58 The aglycone moiety in terpenyl and phenol glycosides can be linked to a  $\beta$ -D-glucopyranose unit or  
59 to a disaccharide (Hjelmeland & Ebeler, 2015). While  $\beta$ -glucosidases [E.C.3.2.1.21] are capable of  
60 cleaving the glycosidic bond between the carbohydrate moiety and the aglycone (Singh, Verma, &  
61 Kumar, 2016), the release of the aglycone from disaccharide glycosides would normally require the  
62 action of other glycosyl hydrolases. Endogenous glycosidases from the grape and the winery  
63 environment have been extensively studied for this purpose; however, they do not tolerate well the  
64 harsh physical and chemical conditions that usually characterize wine processing such as low pH,  
65 high glucose and fructose, and sulphite content. Grape and yeast glycosidases present low activity  
66 under fermentation conditions (Sánchez Palomo, Díaz-Maroto Hidalgo, González-Viñas, & Pérez-  
67 Coello, 2005), therefore commercial preparations are mainly obtained from fungi and have primarily  
68 pectinase activity, with secondary glycosidase activity. Fungal glycosidases have a weak catalytic  
69 specificity which could lead to the hydrolysis of pigment glycosides, and consequent spoiling of  
70 colours and flavours (Hu et al., 2016). In addition, glucose inhibition is a common problem among  
71 fungal  $\beta$ -glucosidases (Chan et al., 2016; Maicas & Mateo, 2005; Sabel, Martens, Petri, König, &  
72 Claus, 2014). Hence, the search for new enzymatic alternatives, more adapted to the wine conditions,  
73 is highly relevant.

74 Extremophiles, organisms very well adapted to extreme environmental conditions unbearably hostile  
75 or even lethal for other forms of life (Rampelotto, 2013), constitute a novel and alternative source of

76 enzymes for industrial application. Extremozymes are generally more capable to withstand industrial  
77 processes in comparison with their mesophilic counterparts (Elleuche, Schröder, Sahm, &  
78 Antranikian, 2014). Among extremophiles, enzymes from halophilic microorganisms tolerate very  
79 high salinity, which normally leads to denaturation, aggregation, and precipitation of most other  
80 proteins. Genomic and structural analyses have established that halophilic enzymes have a higher  
81 pro-ratio of acidic amino acids versus hydrophobic ones and altered hydrophobicity compared to  
82 mesophilic enzymes, which enhance solubility and promote function in low water activity conditions  
83 (DasSarma & DasSarma, 2015). Adaptation to solvents follows the same principle as adaptation to  
84 salt, and thus, halophilic enzymes may be a valid option for biocatalytic processes performed in  
85 water/solvent environments like wines (Alsafadi & Paradisi, 2013).

86 Based on this hypothesis, the extremophilic organism *Halotheothrix orenii* was selected as a source  
87 of a  $\beta$ -glucosidase for possible application in the wine industry. *Halotheothrix orenii* is a true  
88 halophilic and thermophilic bacterium whose unique enzymes are described to have broad pH  
89 stability and ability to deal with high temperatures and a wide range of salt concentrations  
90 (Bhattacharya & Pletschke, 2014). In this work we evaluated the hydrolytic performance of the  $\beta$ -  
91 glucosidase *BglA* described by Kori et al. (Kori, Hofmann, & Patel, 2011) with two glucosides  
92 relevant to floral wine aroma and smoke-taint affected wines and compared it with a commercial  
93 preparation (Rapidase<sup>®</sup> Revelation Aroma).

## 94 **2 Materials and methods**

### 95 *2.1 Chemicals*

96 Water was obtained from a Milli-Q purification system (Millipore, North Ryde, NSW, Australia).  
97 Luria Bertani Broth, Miller and LB Agar, Miller were purchased from Fisher BioReagents<sup>TM</sup>,  
98 Imidazole 99 % was purchased from Alfa Aesar (Fisher Scientific, Bishop Meadow Road,  
99 Loughborough, UK). Citric acid monohydrate, potassium L-tartrate monobasic, D-(+)-glucose 99.5

100 %, D-(-)-fructose European Pharmacopoeia 98% and DL-malic acid  $\geq$  98 % (capillary GC) were  
101 purchased from Sigma-Aldrich (Castle Hill, New South Wales, Australia). Hepes  $\geq$  99.5 % (titration),  
102 sodium chloride, acetone Suprasolv® ECD, ethanol for liquid chromatography LiChrosolv®, tartaric  
103 acid and *p*-nitrophenyl  $\beta$ -D-glucopyranoside (*p*NPG) were obtained from Merck Pty Ltd (Kilsyth,  
104 Victoria, Australia). Rapidase® Revelation Aroma enzymatic preparation was purchased from  
105 Vintessential Laboratories (Dromana, Victoria, Australia). Geranyl glucoside, guaiacyl glucoside, d<sub>7</sub>-  
106 geraniol and d<sub>3</sub>-guaiacol were synthesised in-house.

## 107 2.2 *Microbial strains*

108 The halothermophilic microorganism *Halothermothrix orenii* H 168 was the source of the native  $\beta$ -  
109 glucosidase family 1 *BglA*. The constructed vector (*BglA*-pET45b) was kindly provided to us by Prof.  
110 J. Siegel at UC Davis. *E. coli* BL21 (DE3) was the laboratory strain chosen for the heterologous  
111 expression.

## 112 2.3 *Enzyme expression, purification and lyophilisation*

113 Cells of *E. coli* BL21 (DE3) harbouring the recombinant plasmid were grown at 37 °C in Luria-  
114 Bertani medium supplemented with ampicillin (0.1 mg/mL). When the OD<sub>600</sub> was between 0.6-0.8,  
115 isopropyl  $\beta$ -D-1-thiogalactopyranoside was added as inductor for the overexpression of the enzyme  
116 and the culture left at 30 °C overnight. Cells were harvested at 4500 G, 4 °C, 20 min and the pellet  
117 stored at -20 °C until purification.

118 The cell pellet was resuspended in buffer (HEPES (50 mM), sodium chloride (150 mM), imidazole  
119 (10 mM), pH 7.5) and cells were broken by sonication (6 min cycle, 5s on, 5s off, 50 % amplification).  
120 The lysate was collected by centrifugation at 14500 G, 1 h, 4° C, and the pellet was discarded.

121 The supernatant was then filtered through Millex® PVDF 0.45  $\mu$ m filter before loading it onto a  
122 HisTrap IMAC column previously loaded with NiSO<sub>4</sub> 0.1 M and washed with loading buffer (HEPES  
123 (50 mM), sodium chloride (150 mM), imidazole (10 mM), pH 7.5). The column was washed with  
124 loading buffer until a plateau in the UV<sub>280</sub> absorbance was reached. Low affinity binding proteins

125 were eluted using a step gradient 10 % elution buffer and the protein of interest was eluted using 100  
126 % elution buffer (HEPES (50 mM), sodium chloride (150 mM), imidazole (300 mM), pH 7.5). The  
127 enzyme was dialysed overnight, flash frozen in liquid nitrogen and freeze dried overnight. (Labconco  
128 8 Port Manifold on Consolo Freeze Dryer).

#### 129 2.4 Protein quantification and SDS-PAGE

130 Bradford Protein Assay was used for protein quantification using bovine serum albumin as standard.  
131 Sodium dodecyl sulphate electrophoresis was performed to assess protein purity. Image Studio  
132 Software (version 4.0) was used to quantify the size of the bands corresponding to the proteins of  
133 interest.

#### 134 2.5 Activity test

135  $\beta$ -glucosidase activity was determined spectrophotometrically by adding 10  $\mu$ L of the suitable  
136 enzyme dilution and 290  $\mu$ L of 10 mM *p*-nitrophenyl- $\beta$ -D-glucopyranoside (*p*NPG) in buffer HEPES  
137 50 mM, pH 7.4 at 25 °C. The specific activity (U/mg) was expressed as  $\mu$ mol of product formed per  
138 minute per milligram of protein.

#### 139 2.6 Model wines and juices

140 Two different model wines were selected in representation of a completely sugar dry wine and a table  
141 wine with sugar concentrations typical for Australian commercial wines (Godden, Wilkes, &  
142 Johnson, 2015). Model wine 1 (MW1) consisted of saturated potassium hydrogen tartrate with 10 %  
143 (v/v) ethanol, pH 3.5. Model wine 2 (MW2) consisted of saturated potassium hydrogen tartrate with  
144 10% (v/v) ethanol, 6 g/L glucose, 6 g/L fructose, pH 3.5.

145 Model juice (MJ) was prepared using water, 100 g/L glucose, 100 g/L fructose, 0.2 g/L citric acid, 3  
146 g/L malic acid, 2.5 g/L tartaric acid, pH 3.7. pH was adjusted with tartaric acid 1M in all cases.

## 147 2.7 *Real wines and juices*

148 Two commercially available wines, one white (WW) and one red (RW), and a Chardonnay grape  
149 juice (WJ) produced in-house were used. A 2017 Chardonnay from Riverina, Australia with an  
150 alcohol content of 12.2% v/v, 4.9 g/L glucose and fructose, titratable acid 6.4 g/L and pH 3.35, a 2016  
151 Shiraz from South Eastern Australia with an alcohol content of 13.9% v/v, 5.8 g/L glucose and  
152 fructose, titratable acid 6.2 g/L and pH 3.66 and a Chardonnay juice with total soluble solids 22.6  
153 °Brix (~20 % total sugar content), 52 mg/L SO<sub>2</sub> and pH 3.5. Chardonnay and Shiraz grape varieties  
154 were chosen due to their low monoterpene content.

## 155 2.8 *Enzymatic treatment*

156 In separate 20 mL SPME vials, 3 mL of MW1, MW2, MJ, WW, RW and WJ were spiked with 5 µg  
157 of geranyl glucoside and 5 µg of guaiacyl glucoside. The amount added to each sample of Rapidase®  
158 or BglA was 0.01 mg/mL. The samples were left shaking at 22 °C over different incubation periods  
159 to allow enzymatic hydrolysis. The reaction was stopped by adding 2 mL of saturated CaCl<sub>2</sub>. Internal  
160 standards, d<sub>7</sub>-geraniol and d<sub>3</sub>-guaiacol, were added (2 µg) and the liberated aglycones were analysed  
161 using SPME-GCMS. All experiments were carried out in triplicate.

162 Geraniol and guaiacol calibration curves with a linear range between 0.02-5 µg were performed for  
163 each matrix.

## 164 2.9 *GC-MS analysis of volatiles*

165 A Gerstel autosampler (MPS) (Lasersan Australasia Pty Ltd, Robina, Queensland, Australia) was  
166 fitted with a 2 cm DVB/CAR/PDMS fibre assembly (Supelco, Bellefonte, PA) to sample the  
167 headspace above the stirred sample for 20 min at 35 °C, immediately prior to instrumental analysis.  
168 Analyses were carried out with an Agilent 6890A gas chromatograph and an Agilent 5973 mass  
169 selective detector (Agilent Technologies, Forest Hill, Australia) fitted with a Gerstel autosampler  
170 (MPS). Injection was done in pulsed splitless mode with a pulse pressure of 7.06 psi for 1 min. The  
171 injection liner was a Supelco injection sleeve made of 0.75 mm i.d. deactivated borosilicate glass.

172 The gas chromatograph was fitted with a 30 m x 0.25 mm Agilent J&W DB-35ms Ultra Inert column,  
173 0.25 µm film thickness. The carrier gas was helium, linear velocity was 36 cm/s, and flow rate was 1  
174 mL/min. The oven temperature, was held at 40 °C for 1 min, increased to 240 °C at a 5 °C/min rate,  
175 and held at this temperature for 2 min. The injector temperature was 220 °C, and the transfer line was  
176 held at 240 °C. Positive electron ionisation mass spectra at eV were recorded in SIM mode with *m/z*  
177 69, 81, 93, 99, 109, 121, 123, 124, 127, 128, 136, 154, and 161 with dwell 25 ms (See section 1 of  
178 the supplementary information for geraniol and guaiacol quantifiers and qualifiers for identification  
179 with MS).

180 Mass Hunter software (version B.09.00 Agilent) was used for the quantitative analysis.

181 The hydrolysis percentages were calculated using the following equations:

182 
$$\% \text{ geraniol release} = \left( \left( \frac{\text{amount of free geraniol detected}}{\text{amount of geranyl glucoside added}} \right) \frac{316}{154} \right) \times 100$$

183 
$$\% \text{ guaiacol release} = \left( \left( \frac{\text{amount of free guaiacol detected}}{\text{amount of guaiacyl glucoside added}} \right) \frac{286}{124} \right) \times 100$$

#### 184 2.10 Data analysis

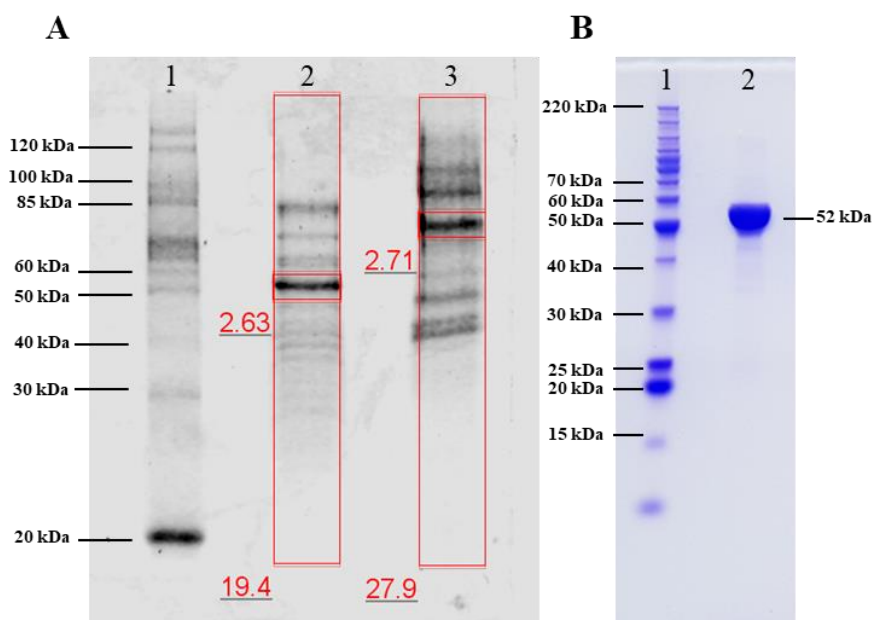
185 For the experiments in model wines (MW1, MW2) and model juice (MJ) two-way analyses of  
186 variance (ANOVA) (GraphPad Prism 8, San Diego, California, USA) were carried out to assess the  
187 effects of enzyme and incubation period on the hydrolysis of glycosides. For the experiments in real  
188 wines (WW, RW) and real juice (WJ) a paired t-test was run to assess the effect of the enzyme.  
189 Significant difference values were calculated in all cases (\*\*\*\* $p \leq 0.0001$ ; \*\*\* $p \leq 0.001$ ; \*\* $p \leq 0.01$ ,  
190 \* $p < 0.05$ ).



### 191 3 Results and discussion

#### 192 3.1 Protein expression, purification, and lyophilisation.

193 *BglA* was expressed with an average yield of 53 mg protein/L of culture. Estimation by quantification  
 194 analysis (using Li-cor Odyssey Fc scanner and software Image Studio version 4.0) suggested that 13  
 195 % of the crude extract corresponded to *BglA* (Fig 1). The activity of the crude extract was found to  
 196 be 2.1 U/mg of total proteins. The enzyme was then purified by metal affinity chromatography, to  
 197 better asses its hydrolytic capacity, and SDS-PAGE was done to assess its purity. For Rapidase®,  
 198 estimation by quantification suggests that 10 % of the commercial preparation would correspond to  
 199  $\beta$ -glucosidases (Fig 1).



200

201 **Figure 1.** A. Quantification of the bands corresponding to *BglA* in the crude extract and to the  $\beta$ -glucosidase in the Rapidase®  
 202 preparation are indicated in red, the signal is expressed in relative fluorescence units (RFU) using Li-cor Odyssey Fc scanner and  
 203 software Image Studio version 4.0), (1) ThermoFisher Scientific PageRuler™ Unstained Protein Ladder, (2) *BglA* in the crude extract  
 204 (5  $\mu$ g) (3)  $\beta$ -glucosidases in Rapidase® (5  $\mu$ g). B. SDS-PAGE after *BglA* purification (1) Invitrogen™ BenchMar™ Protein Ladder (2)  
 205 Pure *BglA* (5  $\mu$ g).

206

207 Following dialysis, *BglA* was lyophilized and stored at 4 °C until needed. An activity assay under  
 208 standard conditions was performed before and after lyophilisation confirming enzymatic stability  
 209 with a specific activity of 5.5 U/mg of protein. Rapidase® was used directly from the commercial

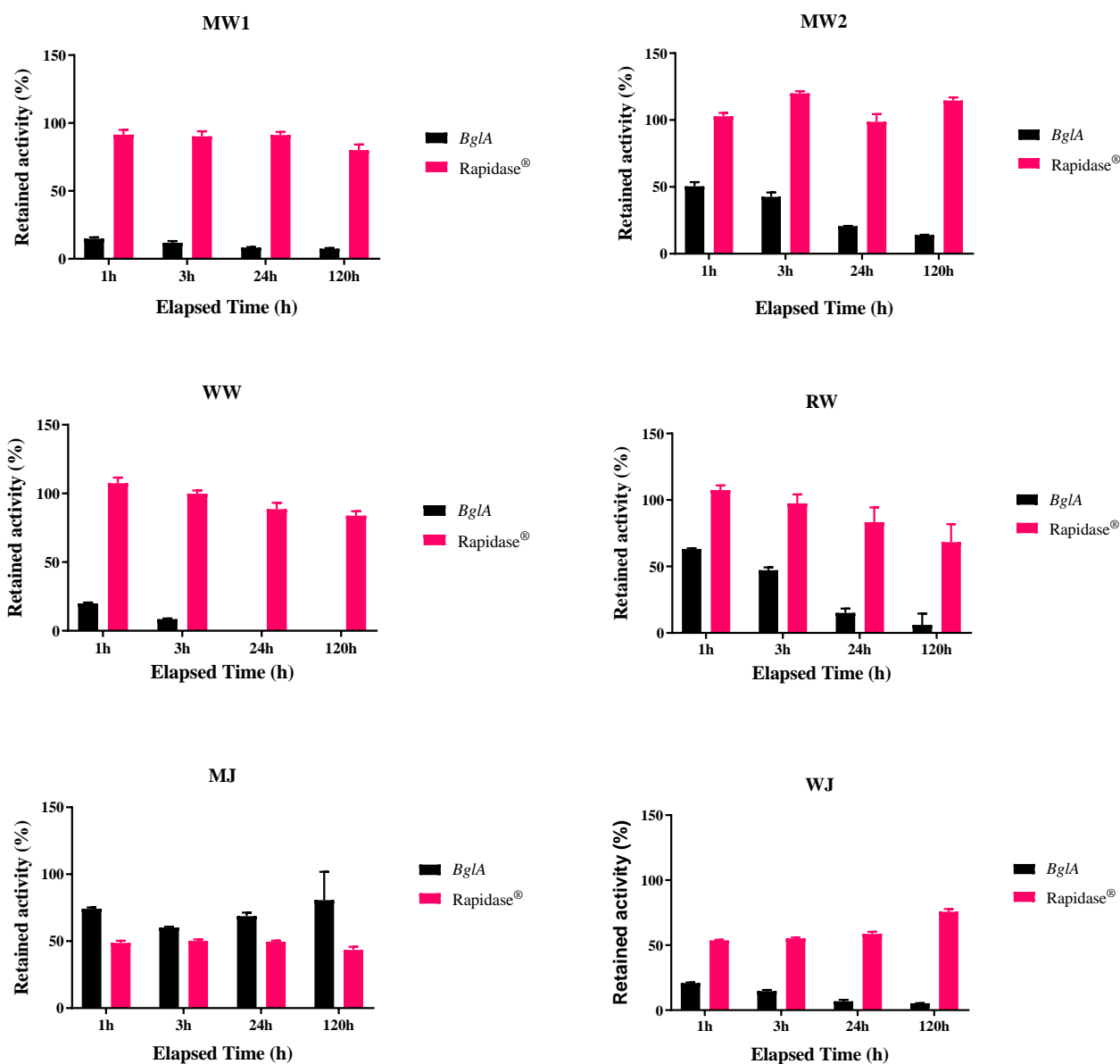
210 packaging with no further treatment. The specific  $\beta$ -glucosidase activity of the commercial  
211 preparation was calculated as 0.16 U/mg of protein.

### 212 3.2 *BglA preliminary assessment in media mimicking wine conditions*

213 As a first assessment of the suitability of *BglA*, a general characterization of the enzyme activity and  
214 stability under different conditions and in buffers mimicking different stages of wine processing was  
215 carried out. The enzyme retained 32 % and 90 % of activity when tested in the presence of 5 % (w/v)  
216 glucose and fructose respectively, and 80 % in the presence of 10 % (v/v) ethanol (See section 2 of  
217 the supplementary information). However, prolonged incubation of the enzyme in the different  
218 conditions, did not affect the enzyme structural integrity and a 100 % recovered activity was observed  
219 in all cases (See section 3 of the supplementary information).

### 220 3.3 *Enzymatic stability*

221 Stability assays of *BglA* and Rapidase<sup>®</sup> were also carried out in more complex media; two model  
222 wine systems (MW1 and MW2) and a model juice (MJ) were selected to mimic operational  
223 conditions. In addition, two real wine matrices (a white, WW, and a red, RW) and a white grape juice  
224 (WJ) were included in the screening to assess the performance and longevity of both enzymes in real  
225 complex matrices. The appropriate amount of lyophilised enzyme was dissolved in the different  
226 systems and incubated for varying periods of time at 22 °C. An activity test was performed at suitable  
227 intervals (1 h, 3 h, 24 h, and 120 h) to assess how the chemical conditions of the matrix (pH, ethanol  
228 and sugars) affect the stability of the enzymes.



**Figure 2.** *BglA* and Rapidase® stability assays in Model wine 1 (MW1), Model wine 2 (MW2), White wine (WW), Red wine (RW), Model juice (MJ) and White grape juice (WJ) incubated at 22 °C during 1 h, 3 h, 24 h and 120 h. Each data point is an average of 3 measurements.

As shown in Figure 2 commercial Rapidase® shows a better stability when incubated in MW1 (10 % ethanol, no sugar, pH 3.5), MW2 (10 % ethanol, 12 g/L glu+fru, pH 3.5), WW (12.2 % ethanol, 4.9 g/L glu+fru, pH 3.35) and RW (13.9 % ethanol, 5.8 g/L glu+fru, pH 3.66), retaining over 60 % activity after 5 days of incubation. *BglA* retains 7 % of activity after 5 days incubation in MW1 and no activity after 24 h in WW. However, after 5 days incubation in MW2, *BglA* shows a retained activity of 14 %, a two-fold increase with respect to MW1. As the sugar content is the only difference between

242 these two model matrices, it appears that fructose and glucose have a protective effect towards *BglA*  
243 stability. The stability of *BglA* improves when incubated in RW, retaining 15 % of activity, which is  
244 linked to the difference in pH between the two systems; 3.35 for WW (white) and 3.66 for RW (red).  
245 On the contrary, Rapidase<sup>®</sup> shows the opposite behaviour with a 15 % drop in activity when incubated  
246 for 5 days in RW in comparison with WW and this could be caused by the higher glucose and fructose  
247 content in the red wine (5.8 g/L for the red wine and 4.9 g/L for the white wine) which negatively  
248 impacts the stability of the commercial preparation.

249 However, in the model juice MJ (no ethanol, 200 g/L of glu+fruc, pH of 3.7) *BglA* is considerably  
250 more stable, retaining around 45% of activity after 120 h incubation. In the same matrix, Rapidase<sup>®</sup>  
251 stability suffers in comparison with its performance in real and model wines, where the pH and the  
252 sugar content are significantly lower, and it compares poorly with *BglA*. In white grape juice (WJ),  
253 Rapidase<sup>®</sup> outperforms *BglA*. WJ has less sugar content and lower pH than MJ which clearly impacts  
254 *BglA* stability.

### 255 3.4 Analytical determination of volatiles released upon enzymatic hydrolysis of glucosides

256 The hydrolytic capacity of *BglA* and Rapidase<sup>®</sup> was evaluated with geranyl and guaiacyl glucoside  
257 by measuring the release of the free volatiles in the gas phase with SPME-GCMS. To keep the  
258 assessment consistent with the stability tests, the catalytic efficiency was also assessed in model  
259 systems and real wines as opposed to simpler buffer solutions. The recommended dosage of  
260 Rapidase<sup>®</sup> for white wines is 1 mg of lyophilised powder per hectolitre of wine, and for red wines 2  
261 mg/hl. However, *BglA* has been used as a purified preparation in all the assays to better assess its  
262 performance. To have consistency among all systems, the effective enzyme quantity has been  
263 determined by Bio-Rad protein assay, and the powders weighed to achieve 0.01 mg of protein per  
264 mL of matrix in all tests.

### 265 3.4.1 Release of volatiles from glucosides in model and real wines

266 Interestingly, despite a lower stability determined for *BglA* (Fig 1), the catalytic efficiency of this  
 267 enzyme in MW1 equals that of Rapidase® in the release of geraniol with no significative differences  
 268 (Table 1). The release of guaiacol by *BglA* is, on the other hand, significantly better after 5 days (97  
 269 %) in comparison with Rapidase® (75 %). The observed drop in the hydrolysed substrate after 8 days  
 270 incubation is a known artefact due to the rearrangement of the terpenes under acidic conditions  
 271 (Hampel, Robinson, Johnson, & Ebeler, 2014; Skouroumounis & Sefton, 2000).

272 When the catalytic performance was assessed in MW2, Rapidase® hydrolytic capacity was  
 273 diminished in comparison with MW1. The difference between MW1 and MW2 is once again the  
 274 sugar content. It is known that glucose is a common inhibitor for many  $\beta$ -glucosidases (De Giuseppe  
 275 et al., 2014) and a content of 6 g/L seems to affect the activity of the commercial preparation. The  
 276 formation of geraniol is complete after 24 h incubation in samples containing *BglA*, however in the  
 277 case of Rapidase® 5 days are required to reach complete hydrolysis, compared with 24 h required in  
 278 MW1. The guaiacol formed in samples containing *BglA* is 62 % after 5 d incubation while with  
 279 Rapidase® the release of guaiacol after the same incubation period is 6 times lower (10 %). The  
 280 results are in line with those obtained in the stability assays. The performance of Rapidase® is affected  
 281 by sugars; probably glucose is causing inhibition of the enzyme. On the other hand, *BglA* tolerates  
 282 very well high sugar contents.

MW1	Substrate	Enzyme	Time ****a	Geraniol released ( $\mu$ g)	% Hydrolysis
	Geranyl glucoside	<i>BglA</i>	24h	2.33 $\pm$ 0.09	96
			5d	2.51 $\pm$ 0.11	$\geq$ 99
			8d	2.19 $\pm$ 0.05	90
		Rapidase®	24h	2.42 $\pm$ 0.03	99
			5d	2.65 $\pm$ 0.15	$\geq$ 99
			8d	2.52 $\pm$ 0.11	$\geq$ 99
	Substrate	Enzyme *b	Time ****b	Guaiaciol released ( $\mu$ g)	% Hydrolysis
	Guaiacyl glucoside	<i>BglA</i>	24h	1.57 $\pm$ 0.07	72
			5d	2.12 $\pm$ 0.010	97
			8d	1.20 $\pm$ 0.27	55
		Rapidase®	24h	0.64 $\pm$ 0.04	29
			5d	1.64 $\pm$ 0.12	75

MW2			8d	1.39 ± 0.07	64
	<b>Substrate</b>	<b>Enzyme ****a</b>	<b>Time *****a</b>	<b>Geraniol released (µg)</b>	<b>% Hydrolysis</b>
	Geranyl glucoside	<i>BglA</i>	24h	2.49 ± 0.08	≥ 99
			5d	2.79 ± 0.07	≥ 99
		Rapidase®	24h	1.33 ± 0.10	55
			5d	2.70 ± 0.10	≥ 99
	<b>Substrate</b>	<b>Enzyme ****b</b>	<b>Time *****b</b>	<b>Guaiacol released (µg)</b>	<b>% Hydrolysis</b>
	Guaiacyl glucoside	<i>BglA</i>	24h	0.77 ± 0.04	35
			5d	1.36 ± 0.03	62
		Rapidase®	24h	0.04 ± 0.00	2
			5d	0.23 ± 0.02	10

**Table 1.** *BglA* and Rapidase® release of geraniol and guaiacol over 24 h, 5 d and 8 d in Model Wine 1 and over 24 h and 5 d in Model Wine 2. \*\*\*\*p ≤ 0.0001; \*\*\*p ≤ 0.001; \*p < 0.05. a=geraniol, b=guaiacol.

In comparison with model wines, real wines constitute a highly complex matrix. Without a doubt, underpinning the specific element which either inhibits or destabilises an enzyme is challenging. Potentially, any physical and chemical characteristic of wine is at play: interactions with other molecules, inhibition by sulphur dioxide, rearrangements between components, low pH, sugar content, phenolic glycosides, etc. (Plank et al., 1993). In all cases, hydrolysis was slower and that is reflected in the results.

Rapidase® shows improved activity in WW (Table 2), while the hydrolytic capacity of *BglA* is very limited. On the other hand, after 5 days incubation in RW, *BglA* releases over 30 % geraniol and over 3 % guaiacol. This improvement of the performance of *BglA* in red wine is probably related to a 0.31 pH units difference and 0.9 g/L sugars between white wine and red wine.

WW	<b>Substrate</b>	<b>Enzyme *****a</b>	<b>Time</b>	<b>Geraniol released (µg)</b>	<b>% Hydrolysis</b>
	Geranyl glucoside	<i>BglA</i>	5d	0.01 ± 0.01	0
		Rapidase®	5d	1.94 ± 0.02	80
	<b>Substrate</b>	<b>Enzyme ****b</b>	<b>Time</b>	<b>Guaiacol released (µg)</b>	<b>% Hydrolysis</b>
	Guaiacyl glucoside	<i>BglA</i>	5d	0.00	0
		Rapidase®	5d	0.24 ± 0.00	11
RW	<b>Substrate</b>	<b>Enzyme ***a</b>	<b>Time</b>	<b>Geraniol released (µg)</b>	<b>% Hydrolysis</b>
	Geranyl glucoside	<i>BglA</i>	5d	0.75 ± 0.06	31
		Rapidase®	5d	2.00 ± 0.07	82
	<b>Substrate</b>	<b>Enzyme *b</b>	<b>Time</b>	<b>Guaiacol released (µg)</b>	<b>% Hydrolysis</b>

Guaiacyl glucoside	BglA	5d	0.07 ± 0.00	3
	Rapidase®	5d	0.23 ± 0.03	11

297

298 **Table 2.** *BglA* and Rapidase® release of geraniol and guaiacol over 5d in White Wine (WW) and Red Wine (RW). \*\*\*\* $p \leq 0.0001$ ;  
299 \*\*\* $p \leq 0.001$ ; \*\* $p \leq 0.01$ ; \* $p < 0.05$ . a=geraniol, b=guaiacol.

### 300 3.4.2 Glycosides release in model and real juice

301 Results in model juice (MJ) (Table 3) highlight an outstanding performance of *BglA* in comparison  
302 with the commercial preparation. While Rapidase® hydrolysis capacity is below 6 % for both  
303 compounds, the percentage of glycosides hydrolysed by *BglA* is over 60 % for geraniol and over 25  
304 % for guaiacol after 5 days incubation, reaching 45 % after 8 days.

305 In the case of grape juice (WJ), after 5 days incubation *BglA* continues to show significantly better  
306 hydrolysis percentage for geraniol: 10 % against 6 % of Rapidase®. The amount of guaiacol liberated  
307 by *BglA* is also slightly higher (2 %) than the one released by Rapidase® (1 %).

MJ	Substrate	Enzyme ****a	Time **a	Geraniol released (µg)	% Hydrolysis
	Geranyl glucoside	<i>BglA</i>	24h	0.94 ± 0.04	39
			5d	1.54 ± 0.04	63
			8d	1.15 ± 0.21	47
		Rapidase®	24h	0.03 ± 0.01	1
			5d	0.07 ± 0.02	3
			8d	0.08 ± 0.02	3
	Substrate	Enzyme ****b	Time ****b	Guaiacol released (µg)	% Hydrolysis
	Guaiacyl glucoside	<i>BglA</i>	24h	0.00	0
			5d	0.55 ± 0.11	25
			8d	0.98 ± 0.01	45
		Rapidase®	24h	0.00	0
			5d	0.04 ± 0.00	2
			8d	0.12 ± 0.04	5
WJ	Substrate	Enzyme **a	Time	Geraniol released (µg)	% Hydrolysis
	Geranyl glucoside	<i>BglA</i>	5d	0.26 ± 0.01	10
		Rapidase®	5d	0.14 ± 0.01	6
	Substrate	Enzyme	Time	Guaiacol released (µg)	% Hydrolysis
	Guaiacyl glucoside	<i>BglA</i>	5d	0.03 ± 0.01	2
		Rapidase®	5d	0.02 ± 0.01	1

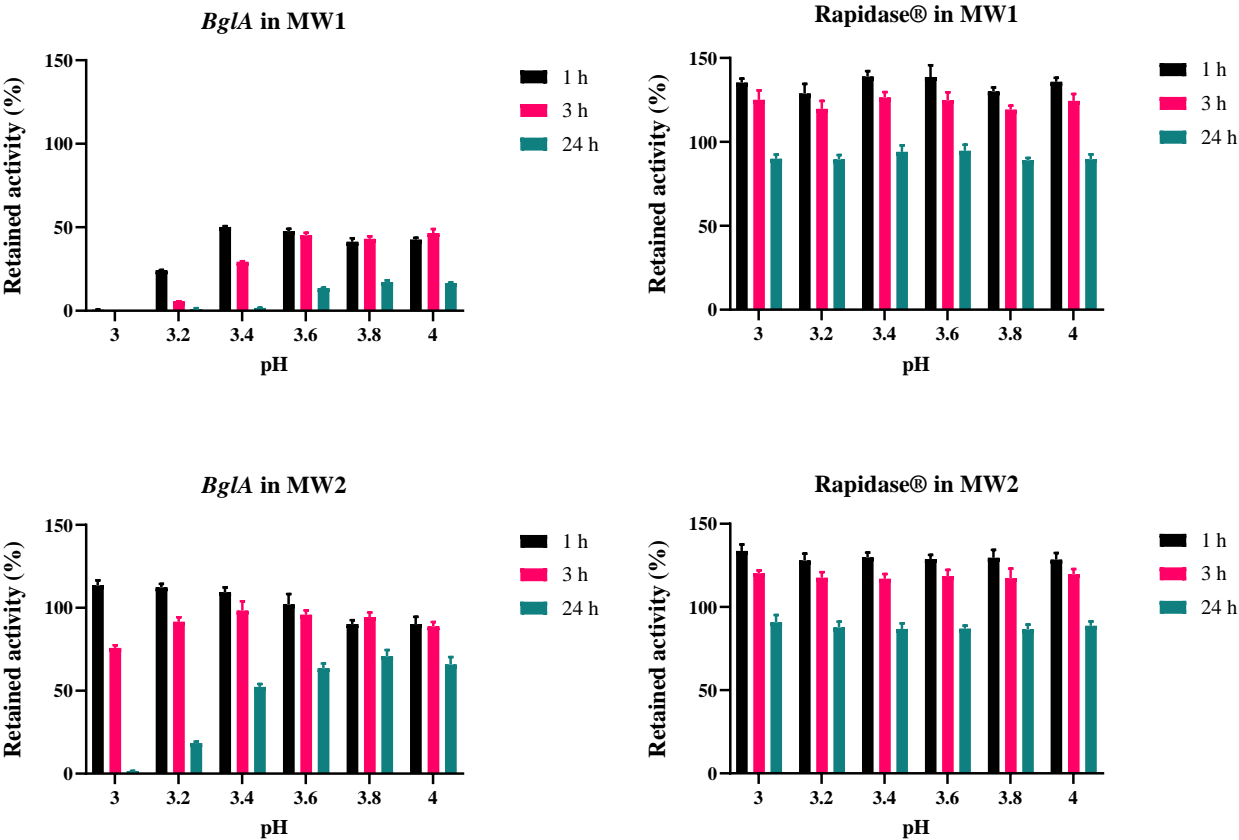
308

309 **Table 3.** *BglA* and Rapidase® release of geraniol and guaiacol over 24 h, 5 d and 8 d in Model juice (MJ) and over 5 d in real White  
310 Juice (WJ). \*\*\*\* $p \leq 0.0001$ ; \*\*\* $p \leq 0.001$ ; \*\* $p \leq 0.01$ , \* $p < 0.05$ . a=geraniol, b=guaiacol.

311 3.5 Detailed pH stability assay in MW1, MW2 and MJ

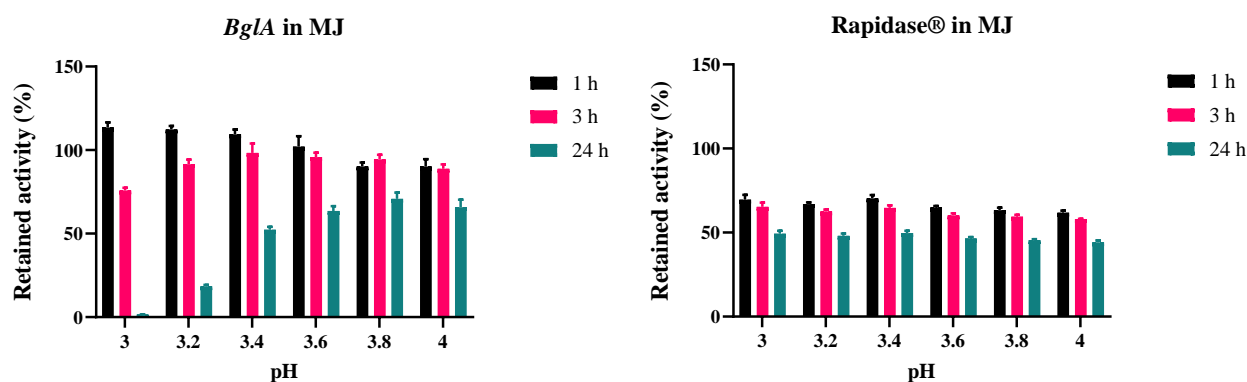
312 The results above show that *BglA* loses stability between pH 3 and 4. To further narrow the pH fork  
313 causing it, a more accurate stability assay of *BglA* and Rapidase® was carried out with 0.2 pH intervals  
314 between pH 3 and 4 in MW1, MW2 and MJ at 22 °C. Retained activity was measured after 1 h, 3 h,  
315 24 h and 120 h, same intervals as in the enzyme stability experiment in different matrices summarised  
316 in Figure 2. Unfortunately, measures after 120 h incubation were no longer reliable, probably due to  
317 sample concentration by water loss (results not shown).

318



319





**Figure 3.** BglA and Rapidase® pH stability assays in Model wine 1 (MW1), Model wine 2 (MW2) incubated at 22 °C during 1 h, 3 h and 24 h. Each data set is an average of 3 measurements.

*BglA* loses virtually all activity within 24h of incubation in MW1 and MW2 at a pH lower than 3.6. However, in MJ at pH 3.2, the enzyme still retains 20 % of its activity after the same incubation time. The experiments clearly show that the more sugar the matrix contains, the higher activity *BglA* retains, at all pHs. Rapidase® is clearly independent on pH and the preparation is equally stable between 3 and 4, however, the sugar content present in MJ reduces its activity by almost 50 % very rapidly. These results confirm once again the suitability of *BglA* for matrices with high content of sugars, for example during the maceration or other early stages of the winemaking, previous to the fermentation. Certainly, *BglA* displays great potential for its application in juices. In this work only grape juice has been tested but the results in model juice suggest that any other fruit juice would be a suitable matrix for *BglA*, especially those having a pH over 3.5, like some apple, orange or lemon juices (Yan et al., 2018).

Finally, it is worth to highlight that amounts of freeze-dried protein (mg), and not specific activities (U/mg) have been compared in this study. Due to the lower specific activity of Rapidase® under the same standard conditions, higher amount of freeze-dried preparation of Rapidase® would be required to achieve the same results as *BglA*. Clearly Rapidase® is stable, at least at low sugar content, and when the results are normalised per U of activity its performance is higher, however, from an industrial cost-effective point of view *BglA*, offers both as a crude preparation and in its purified form,

341 13-fold and 34-fold higher activity than the commercial preparation, which results in less quantity of  
342 catalyst needed during the wine-making process (or shorter processing times).

#### 343 4 Conclusions

344  $\beta$ -Glucosidases are used in the wine industry to enhance the aroma of wines and have been proposed  
345 to remediate smoke taint defects. The hydrolytic capacity of *BglA* for geraniol glucoside and guaiacol  
346 glucoside was significantly better than the commercial preparation in all the tested matrices with high  
347 sugar content, where the performance of Rapidase<sup>®</sup> decreases considerably. In fact, *BglA* high activity  
348 in the presence of glucose, outperforms also other reported fungal  $\beta$ -glucosidase such as the one *W.*  
349 *anomalus*, which retains only 25 % of activity in the presence of 4 % (w/v) glucose (Sabel et al.,  
350 2014), or that from a *A. niger* which retains 64 % of activity when 1 g/L glucose (0.1 % w/v) is added  
351 to the reaction but only 2 % when 100 g/L glucose (10 % w/v) is used (Martino et al., 2000). *BglA* is  
352 also stable and active in the presence of ethanol as it can be observed from the results in model wines.  
353 On the other hand, the activity of *BglA* is very pH dependent and in matrices with a pH below 3.5,  
354 like real white wine, the enzyme is not able of hydrolysing glycosides. Future work on enzyme  
355 immobilization will be carried out to compare the enzymatic stability at low pH and try to improve  
356 it.

357 Great tolerance to sugar content along with improved performance over a broad pH range makes *BglA*  
358 an excellent candidate for aroma amelioration and mitigation of smoke taint in grape juices and wines,  
359 especially during the early stages of the winemaking process when the sugar content and the pH range  
360 is higher than in fermented wines. Future work will also include testing the enzyme in other model  
361 and real wines as well as a sensory evaluation of treated wines.

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## 368    **6    Abbreviations used**

369    ANOVA, analysis of variance; CIS, cooled inlet system; DVB/CAR/PDMS  
370    divinylbenzene/carboxen/polydimethylsiloxane, *E.coli*, *Escherichia coli*; GC, gas chromatography;  
371    g, gram; hl, hectolitre; IPTG, Isopropil- $\beta$ -D-1-thiogalactopyranoside; MW1, model wine 1; MW2,  
372    model wine 2; MJ, model juice; MPS, multipurpose sampler LB, Luria-Bertani; multipurpose  
373    sampler; MS, mass spectrometry;  $\mu$ g, microgram; OD, optical density; *p*NPG, paranitrophenol- $\beta$ -D-  
374    Glucopyranoside; RW, red wine; rpm, revolutions per minute; SIM, selected ion monitoring; SPME-  
375    GCMS, solid-phase microextraction, gas chromatography mass spectrometry; VP, volatile phenols;  
376    v/v, volume volume; w/v, weight per volume; WJ, white juice; WW, white wine.

## 377    **7    Conflict of interest**

378    The authors declare no conflict of interest in publishing this work.

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